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NEUROLOGICAL PROCESSES OF MOVEMENT CONTROL: A REVIEW[1]

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While an understanding of the control of movement is central to significant areas of physiotherapy practice, a complete grasp of the processes involved has proved to be both tantalizing and elusive. The complexity of integrative activity between sensory and motor systems appears to be beyond the reach of traditional methods of experiment. The resources of both psychophysical and neurophysiological methodology are even yet insufficiently refined to yield all that remains to be understood.

It is hoped here, however, to clarify current thinking on the extent to which these neurological processes are understood. While it is recognized that central and peripheral control are interdependent, for simplicity this paper is organised under headings of cerebral control and feedback, and spinal pathways and their cerebral connections. Bimanual coordination is a particular type of skilled movement and is treated separately.

CEREBRAL CONTROL AND FEEDBACK

According to Fischer (1967), from the point of view of the neurologist, the processes which occur during skill learning involve the subject's acquiring the "most economical use of differential facilitation and inhibition of the various muscles involved in the specific task". He claims that "the days have passed since it was generally assumed that the primary motor areas of the cerebral cortex alone were responsible for volitional movements". "The concept [of hierarchical functional organization of the C.N.S.] has gained ground and is now so generally accepted that one does not even dare to make a judgement as to which structure in the C.N.S. is the most important in voluntary skilled motor activity." Similarly, Herman (1970), Shambes and Waterland (1973) and Waterland (1967) maintain that "the basis of coordinated motor activity appears to be in the structural and functional organization of the C.N.S.".

A sound explanation of the control effected in skill learning is offered by Fischer *(op. cit.)* and is summarized below. The theoretical views of Shambes and Waterland *(op. cit.)* are consistent with those of Fischer, although not as developed in depth and scope.

Fischer uses a concept of a subcortical "centrencephalic" system of integration which is a "diffused system high in the brain stem, extending into diencephalic structures, including the thalamus". This system is considered to be responsible for "voluntary" commands and from this system impulses are sent to subcortical motor areas which then of themselves might be able to activate spinal cord activity for non-learned movements of infants and to the cortical motor areas of the cerebellum, activating them. Simple movements can occur as a consequence of the activity of cortical motor areas which is brought about simultaneously *via* subcortical motor mechanisms and extrapyramidal and pyramidal pathways. For skilled performance, feedback mechanisms are needed. Hein (1972) and Held (1965) both endorse this statement quite strongly; they are each convinced that the motor sensory feedback loop has a fundamental role in movement control.

Fischer details three types of feedback — the first is a gamma motor loop system which

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attenuates the servomechanisms represented by the intrafusal muscle receptors affecting the activity of the spinal cord, of the paleocerebellum and bulbomesencephalic formation. Partridge indicated this possibility in 1961. In 1972 Smith *et al.* studied voluntary arm movements in man and concluded that linkage of alpha and gamma motorneurons at supraspinal centres is necessary for optimal coordination of moderately rapid elbow actions, and that the gamma loop contributes to the precise temporal patterning of alpha motorneurons.

Further control of skilled movements is exerted by articular as well as by exteroceptive receptors of the skin, modifying spinal cord activity as well as thalamic and cerebral sensorimotor cortex function.

Two further servomechanisms loop together:

(a) sensorimotor cortex, bulbomesencephalic formation, thalamus, sensorimotor cortex; and
(b) sensorimotor cortex, corpus striatum, sensorimotor cortex.

The system of spinocerebellar tracts, cerebellar cortex, dentate nucleus, motor cortex modulates further by either decreasing or intensifying a movement during its execution under the influence of the incoming proprioceptive impulses from the muscles involved.

In the regulation of skilled movements and depending on the overall situation, sensory input due to vision and hearing often has considerable influence on midbrain, thalamic and cerebral cortex activities.

Studies on individual motor unit control were made by Basmajian (1967), Lloyd and Leibrecht (1971) and Zappala (1970). On the basis of his experimental evidence, Basmajian postulates that "although skills learned . . . at first depend on aural and visual feedback from muscles, the controls are learned so quickly, are so exquisitely and so well retained after initial feedbacks are eliminated, that one cannot help believing that fundamental processes are involved". He therefore hypothesizes a "proprioceptive memory that is almost certainly integrated in the spinal cord".

Lloyd and Leibrecht *(op. cit.)* and Zappala *(op. cit.)* agree with Basmajian that control of single motor units is not essentially the function of feedback; all agree however that training is a positive factor in enabling an individual to isolate and to control single motor units. Lloyd and Leibrecht demonstrated that in the absence of visual and auditory electromyography (E.M.G.) oscilloscope feedback some subjects retain skills, and reasoned that, in the absence of additional cues, a subject must concentrate on and use the stimuli produced by the muscle contraction.

Herman *(op. cit.)* found that motor learning could take place without somatic stimuli but the latency of acquisition was markedly delayed.

The situation is summed up nicely by Angel *et al.* (1971) who, with experimental confirmation of their own hypothesis, suggest that errors can be amended by a central mechanism which does not require sensory feedback. In early learning peripheral information (such as feedback) is important but becomes redundant as soon as a central motor programme has been established. This is consistent with the statements made by Pew (1966) and Wyke (1971).

The concept of the "central mechanism" alluded to by Angel *et al.* is further elaborated by Gyr (1972) who, in reporting animal studies, suggested a purely central feedback mechanism which returns information concerning future movements to the C.N.S. before the impulses which will produce these movements have reached the periphery, thereby allowing the animal to know the position of the limb even when there are no peripheral sensations. They speculated that the mechanism seems to involve afferent collaterals from the medullary pyramidal tracts to the gracile and cuneate nuclei, and thence back to the cerebral cortex. They concluded, significantly, that organisms do appear to possess systems at the level of the C.N.S. which tell them about their own activity. Moreover, this central mechanism is essential for the conduct of response-contingent voluntary activity (as all physiotherapy skills might be classified).

The findings on visually guided behaviour by Hein *(op. cit.)* confirm Gyr's evidence. Held *(op. cit.)* also pointed to the importance of extraoptic, central parameters in perception. The limbic-midbrain circuits are

probably not too important for the perfect execution of learned skilled motor actions, but are probably more important in motor learning by influencing motivation, and indirectly, attention. The reticular formation is also generally accepted to be important in attention (Fischer, *op. cit.*).

The supposition is put forward by Murphy *et al.* (1973) that the two parameters of movement, position and velocity, are critical. They posited that information about these parameters occurs *via* a feedback system provided through cerebellar purkinje cells (and that these cells respond only to dynamic and not to static displacement of individual muscles). In this way comparison of intention and result occurs. Shambes and Waterland *(op. cit.)* agree with Murphy *et al.* about movement parameters although they prefer space and time concepts. They postulated that skilfully executed movement patterns are composed of both postural and volitional components which have to be properly coordinated in both space and time.

SPINAL PATHWAYS AND THEIR CEREBRAL CONNECTIONS

Postural adjustments which occur automatically in trunk and limb musculature are believed to be subserved primarily by subcortical pathways. On the other hand volitional motor activity seems to be associated primarily with more complex or skilled movement and is thought to be centrally controlled by the cerebral cortex. Shambes and Waterland *(op. cit.)* investigated the pathway control and emerged with some quite specific and certainly interesting findings. Using E.M.G. studies they confirmed evidence that "corticospinal and corticorubrospinal tracts are related to the motor system innervating distal muscles of the upper and lower extremity and flexor muscles in general". They found that stimulation of these tracts produces flexor movements and complex skilled patterns which are composed mainly of flexion components.

The reticulospinal and vestibulospinal tracts, on the other hand, are associated with the motor system which influences postural movement. These tracts are known to be facilitatory to muscles of the trunk and to proximal segments of the upper and lower extremity and to extensor muscles in general.

It is further elucidated by Shambes and Waterland that type A or pale muscle fibres are associated with more centrally directed movements and are used in phasic types of motor activity. The *biceps brachii* muscle has a high concentration of such fibres and is usually identified as a muscle which plays a major role in fine, manipulative actions of the body. Muscles used in highly skilled activity are also believed to be more heavily endowed with muscle spindles than muscles used in more gross type movement patterns. Red or tonic muscle fibres are found in postural and extensor muscles such as *triceps brachii.* The fewer the muscle fibres per motor unit within a given muscle, the more elaborate that muscle's movements will be.

There is experimental evidence of motor innervation contraction times presented by Emonet-Denand *et al.* (1971) which can be explained convincingly by using the hypothesis and findings of Shambes and Waterland.

BIMANUAL COORDINATION

A special category of skilled movement relevant to psychomotor skills is that of bimanual coordination, the underlying mechanisms of which are implied in soft tissue and joint manipulation as well as in neurological treatment principles in physiotherapy.

The ability to perform tasks that require simultaneous responses with more than one body member (both hands, both feet, or hands and feet) constitutes a behavioural phenomenon distinct from other motor skills (Fleishman and Hempel, 1956). Furthermore, "the mechanisms governing bimanual coordination are not well understood" (Cohen, 1971). Cohen also pointed out a fact which is not noted elsewhere but which Fleishman and Hempel adumbrated: that mechanisms which coordinate continuous movement sequences may differ from those which synchronize rapid release movements.

Cohen studied identical voluntary movements in upper limbs performed synchronously when homologous and non-homologous muscles were simultaneously active. He expected that the elaboration of the movements of each limb might entail processing of movement derived kinesthetic feedback from each of the limbs, and that the capacity of a

central processing mechanism might be exceeded when simultaneous processing of input from two sources was necessary.

When the simultaneous movements are performed by non-homologous muscles, central processing of movement derived feedback from both limbs would be required for continued elaboration of bimanual movement.

Bimanual movement control in skilled motor performance is explained by Keele (1968) as a potent sensorimotor control in ipsilateral arms. However, Cohen *(op. cit.)* in a general way, and Fischer *(op. cit.)* disagree with Keele. Even though each of the cerebral hemispheres has its own learning and memory processes, Fischer, on the basis of monkey experiments, was led to speculate on the importance of cerebral commissures for the bimanual coordinated acquisition of skills.

In endeavouring to go beyond Fischer's explanation, Wyke *(op. cit.)* clinically investigated patients with (R) and (L) sided cerebral lesions. She suggested that it is possible for impairment of bimanual coordination in patients with (L) sided lesions to stem not only from impairment of sensorimotor function in the two arms but also from the breakdown of the programme underlying the organization of individual movements. She then showed that patients with (L) sided lesions make initial satisfactory sensorimotor adaptions to a new task, but that further improvement in performance is limited by inability to integrate the separate movements required into an adequately coordinated pattern. This is contrasted in patients with (R) sided lesions when the learning pattern is similar to normal subjects, thus suggesting only minor impairment of processes of initial adaption whose final performance indicates an adequate degree of coordination of the different components in the total performance.

This observation implies that the left cerebral hemisphere is dominant in the control of voluntary movements involving mutual dependence and continuous interaction of (L) and (R) arms. Wyke summarized that (L) sided cerebral lesions produce ipsilateral as well as contralateral deficits, while (R) sided lesions produce contralateral deficits only. Further research is needed to understand the effect of (L) sided lesions on sensorimotor programmes but Wyke hints that the parietal region rather than the frontal or temporal regions of the (L) cerebral cortex may be important in motor and sensorimotor performance, and that it may also be where motor programming occurs.

Wyke's findings provide a cogent introduction to the understanding of bimanual coordination in humans. Her studies and conclusions have a distinct advantage over Cohen's animal studies for phylogenetic reasons and over those of Cohen and Fischer by virtue of her specific demonstrations which are consistent with the hypotheses of all three.

CONCLUSION

It may be noted from the foregoing discussion that much is now known about the control of skilled movement. However, the neurophysiological processes occurring during acquisition of skill are not fully understood at this time. Indeed, attempts to discover literature on that particular aspect have been unsuccessful to date.

Investigation into the changes occurring neurophysiologically and biochemically during skill acquisition would be a fascinating venture, holding also the exciting prospect of finding answers to questions about processes fundamental to all movement. For example, what level of sensorimotor integration predisposes to the acquisition of successively difficult perceptual motor tasks? If this integration is lacking, how might it be diagnosed? And how could it be most efficiently and accurately facilitated? A commendable contribution to the understanding of sensorimotor integration and dysfunction in children has been made by Ayres (1972), but elucidation of these processes in adults has still to be attempted. One is led ineluctably to neurophysiology and biochemistry for answers to these clinical dilemmas.

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